

W PHYSICS AT LEP2

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In five years of operation (1996-2000) the four LEP2 experiments collected roughly 3 fb^{-1} of data from e^+e^- collisions at centre-of-mass energies between 161 and 207 GeV, yielding a total of about 40000 W-pair events. The analysis of the LEP2 W-pair production rates and kinematics has allowed fundamental new measurements of the electroweak model to be performed, most notably: (i) the first determination of gauge boson self couplings, (ii) direct measurements of W decay couplings to all fermions, and (iii) a direct measurement of the W mass with a $40 \text{ MeV}/c^2$ precision, comparable to hadron collider and indirect determinations.

1 W-pair cross section

Pair-production of W bosons is of great importance in the Standard Model (SM) of electroweak interactions¹, where the non-abelian nature of the SU(2) group leads to three-line (TGC) boson vertices that play a crucial role in the W-pair production. The LEP2 data sample of 700 pb^{-1} per experiment at $\sqrt{s}=161\text{-}207 \text{ GeV}$ allowed to collect about 10^4 W-pairs per experiment, identifying these events in all their final states, leptonic and hadronic. The results for the total W-pair cross sections as a function of the centre-of-mass energy² are shown in Fig. 1, and are in overall agreement with SM predictions at the level of 1%. As it can be seen, the LEP2 W-pair cross section measurement alone represents a stunning proof of the presence of both the WWZ and WW γ couplings dictated by the electroweak SU(2) \otimes U(1) gauge structure.

2 W couplings to gauge bosons

The structure and magnitude of WWZ and WW γ couplings are measured fitting the W-pair event rates and the angular distributions of the W production and decay axes². The most general Lorentz-invariant WWV vertex (V= γ, Z) can have seven complex couplings

$$g_1^V \quad \kappa_V \quad \lambda_V \quad g_5^V \quad g_4^V \quad \tilde{\kappa}_V \quad \tilde{\lambda}_V$$

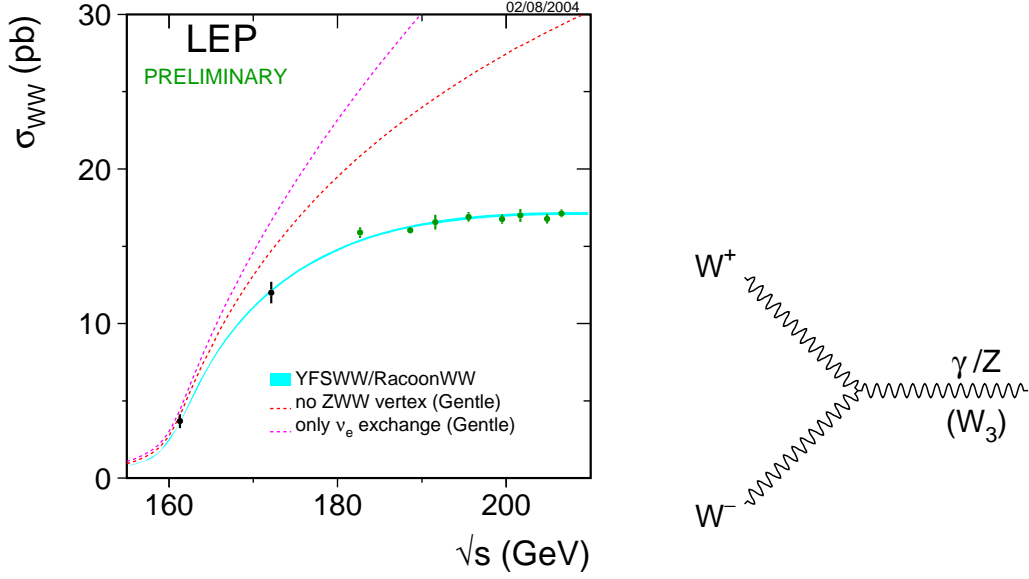


Figure 1: Total W -pair cross-sections measured at LEP at $\sqrt{s}=161\text{-}207$ GeV, compared to SM predictions. The two dashed curves show the predicted W -pair cross section in the absence of the WWZ and $WW\gamma$ couplings shown on the right.

making up a total of 28 parameters for both WWZ and $WW\gamma$ vertices. In the $SU(2)\otimes U(1)$ model we expect $g_1^V = \kappa_V = 1$ for both $V=\gamma$ and $V=Z$, while all other real and imaginary parts are expected to vanish. A fit to ALEPH data only to all 28 parameters³ leads to

$$\begin{aligned} \text{Re}(g_1^\gamma) &= 1.123 \pm 0.091 & \text{Re}(\kappa_\gamma) &= 1.071 \pm 0.062 \\ \text{Re}(g_1^Z) &= 1.066 \pm 0.073 & \text{Re}(\kappa_Z) &= 1.065 \pm 0.061 \end{aligned}$$

and all other 24 coupling parameters consistent with zero, within uncertainties ranging from 0.035 to 0.250. The result of this fit shows how clearly the W -pair data has revealed the $SU(2)\otimes U(1)$ structure of the gauge self-couplings.

A more constrained fit of all LEP2 data, in search of anomalous contributions to TGC, to the three couplings that conserve separately C and P, $U(1)_{\text{em}}$, and global $SU(2)_L \otimes U(1)_Y$, yields²

$$\kappa_\gamma = 0.984 \pm 0.045 \quad \lambda_\gamma = -0.016 \pm 0.022 \quad g_1^Z = 0.991 \pm 0.021,$$

revealing again no deviation from the SM expectations.

3 W decay couplings

Given the possibility to classifying all W decays modes, the LEP2 W -pair sample has allowed the first direct measurement of all leptonic and hadronic W decay branching ratios, as

$$\begin{aligned} B(W \rightarrow qq) &= 67.49 \pm 0.28\% \\ B(W \rightarrow e\nu) &= 10.66 \pm 0.18\% \\ B(W \rightarrow \mu\nu) &= 10.60 \pm 0.15\% \\ B(W \rightarrow \tau\nu) &= 11.41 \pm 0.22\% \end{aligned}$$

where the hadronic decay fraction $B(W \rightarrow q\bar{q})$ is determined under the assumption of lepton coupling universality $B(W \rightarrow e\nu) = B(W \rightarrow \mu\nu) = B(W \rightarrow \tau\nu) = (1 - B(W \rightarrow q\bar{q}))/3$. In the case of lepton non-universality, it can be noticed that the tau decay fraction is currently about three sigmas larger than the electron-muon average.

The above results can be interpreted as a test of the lepton-quark universality of charged currents ($g_q/g_\ell = 1.000 \pm 0.006$), and of the lepton family universality of charged currents ($g_\mu/g_e = 0.997 \pm 0.010$, $g_\tau/g_e = 1.034 \pm 0.015$, $g_\tau/g_\mu = 1.037 \pm 0.014$). The W hadronic decay fraction can also be interpreted as a test of the unitarity of the CKM quark mixing matrix, in the first two families as $\sum |V_{ij}|^2 (i = u, c; j = d, s, b) = 2.000 \pm 0.026$, and from this extract the Wcs coupling amplitude $|V_{cs}| = 0.976 \pm 0.014$, without CKM unitarity assumptions.

4 W mass

4.1 W mass from threshold cross section

At the start of LEP2 about 10 pb^{-1} of data per experiment were recorded near the W-pair production threshold ($\sqrt{s} \simeq 161 \text{ GeV}$), where the production cross section alone is very sensitive to the m_W value. From the cross section determination an independent measurement of the W mass has been obtained to be $m_W = 80.40 \pm 0.20 \text{ GeV}/c^2$, where the large uncertainty is due to the limited statistics of the data sample.

4.2 W mass from kinematic reconstruction

The W invariant mass is reconstructed event-by-event in all qq $\bar{q}\bar{q}$ and qq $\ell\nu$ decays of W-pairs, from the kinematics of the visible decay particles. The resolution of the W mass peak is improved by applying a kinematic fit imposing energy-momentum conservation constraints, leading to mass distributions as those shown in Fig. 2.

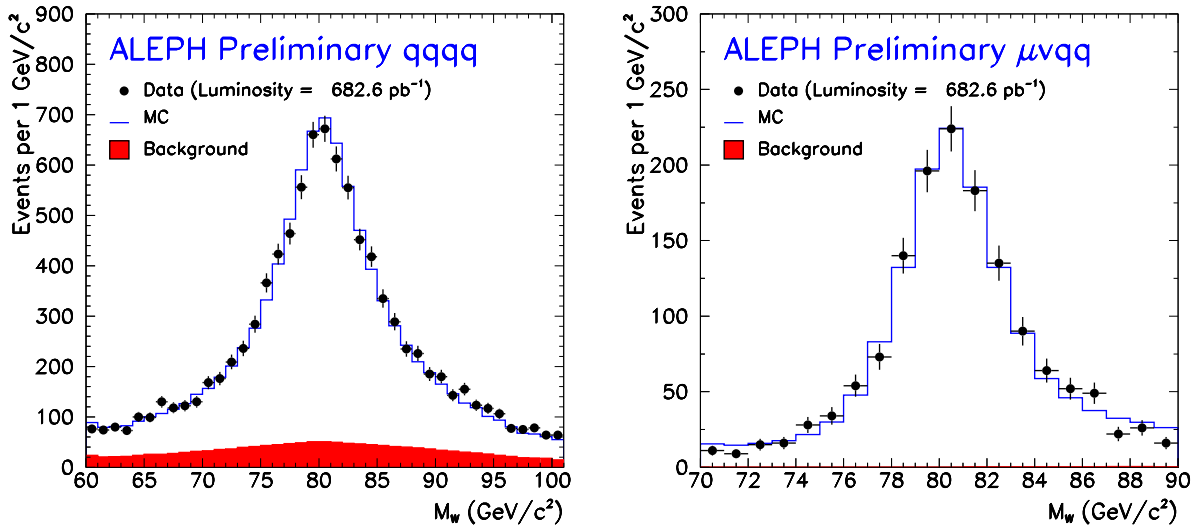


Figure 2: ALEPH reconstructed W mass distributions after applying energy-momentum conservation constraints, in the fully hadronic channel (left), and in the semi-leptonic muon channel (right).

The m_W value is extracted from the W mass distributions with different methods as fits with a probability density function (p.d.f.) calibrated with Monte Carlo simulations, or Monte Carlo re-weighting techniques using the measured masses and their errors as inputs². The m_W values

and systematic uncertainties are evaluated separately for each W-pair decay topology, (qqqq, $e\nu qq$, $\mu\nu qq$ and $\tau\nu qq$) and the final m_W values is obtained by combining the measurement from the individual channels. The most recent combined result from the LEP2 data is

$$m_W = 80.412 \pm 0.042 \text{ GeV}/c^2$$

where the weight of the fully hadronic (qqqq) channel is only 10% because of large uncertainties coming from possible final state interactions (FSI) effects between the two W hadronic decay products. Recent prospects to reduce the FSI uncertainty on m_W in the hadronic channel from 100 to 40-50 MeV/ c^2 should bring down the combined error on m_W from 42 to 35-38 MeV/ c^2 . The current LEP2 determination and other direct and indirect measurements of m_W are shown in Fig. 3.

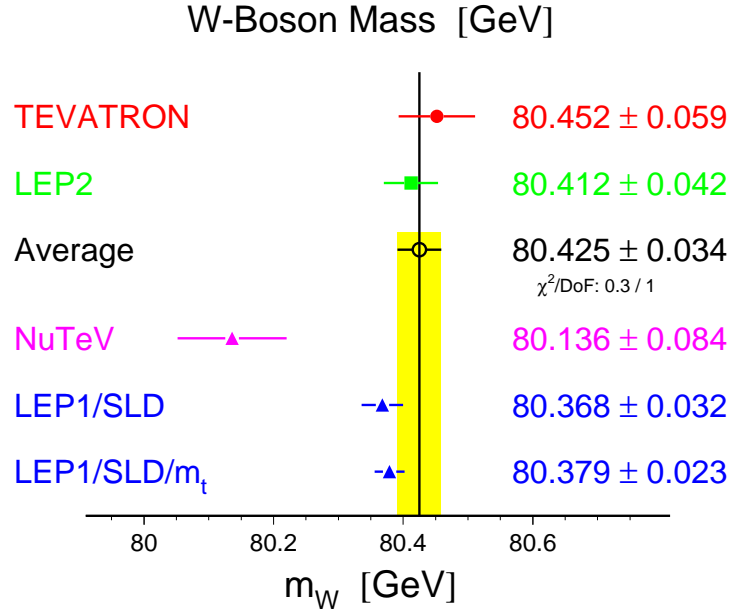


Figure 3: Comparison of W mass measurements. Results from the direct measurements from TEVATRON and LEP2 data² are shown on the top. Indirect constraints from other electroweak measurements are shown on the bottom². Separately, the NuTeV determination⁴ is 2.8 sigmas lower than the direct determinations.

References

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